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Response of Single Junction GaAs/GaAs and GaAs/Ge Solar Cells to Multiple Doses of 1 MeV Electrons

D. L. Meier, J. R. Szedon, and J. Bartko
Westinghouse R&D Center
Pittsburgh, PA 15235

M. A. Chung
Air Force Wright Aeronautical Laboratories
Wright-Patterson Air Force Base, OH 45433

Summary

A comparison of the radiation tolerance of MOCVD-grown GaAs/GaAs cells and GaAs/Ge cells was undertaken using 1 MeV electrons. Both types of cells were fabricated by the Applied Solar Energy Corporation under contract to the Air Force. The electron radiation was delivered in doses of $1 \times 10^{16}\text{cm}^{-2}$ up to a total dose of $1 \times 10^{17}\text{cm}^{-2}$ for GaAs/GaAs and a total dose of $7 \times 10^{16}\text{cm}^{-2}$ for GaAs/Ge. Following each dose of $1 \times 10^{16}\text{cm}^{-2}$, the cells were annealed at either 250°C or 300°C for one hour in nitrogen. It was found that the radiation tolerance of the GaAs/Ge cells was superior to that of the GaAs/GaAs cells. Because the primary effect of radiation is to decrease the diffusion length of the minority carriers in the emitter and the base of the cell, the short-circuit current density (J_{sc}) is the parameter affected most directly.

For GaAs/Ge cells annealed at 250°C, the value of J_{sc} measured under AM0 conditions decreased from 29.1 ± 1.0 mA/cm^2 as-received to 19.6 ± 1.2 mA/cm^2 after a total dose of $7 \times 10^{16}\text{cm}^{-2}$. Thus, 67% of the initial value of J_{sc} was retained. For GaAs/GaAs cells annealed at 250°C, 56% of the initial value of J_{sc} was retained after the same dose, as the measured J_{sc} decreased from the initial value of 28.8 ± 0.8 mA/cm^2 to 16.0 ± 1.0 mA/cm^2. The results were similar for cells annealed at 300°C. After accumulating a total electron dose of $7 \times 10^{16}\text{cm}^{-2}$, the GaAs/Ge cells retained 75% of their as-received value of J_{sc} (29.3 ± 1.0 mA/cm^2 to 21.9 ± 1.0 mA/cm^2), while the GaAs/GaAs cells retained just 60% of their as-received value (28.8 ± 0.3 mA/cm^2 to 17.4 ± 0.3 mA/cm^2).

Similar results were obtained for the efficiency of the two types of cells, although the initial efiiciency of the GaAs/Ge cells (13.4 ± 1.4%) was less than that of the GaAs/GaAs cells (16.5 ± 0.8%) This difference in initial efficiency exists because the GaAs/Ge cells had a low fill factor (0.617 ± 0.038) associated with tbe interface between the GaAs layer and the Ge substrate while the GaAs/GaAs cells had a normal value of fill factor (0.774 ± 0.030).

ln an attempt to examine in greater detail the causes for the observed radiation behavior, preliminary DLTS and EBIC measurements were made. Two deep levels were found to result from the electron radiation, and the concentration of these levels was reduced significantly by the annealing. The EBIC measurements, along with cross-sectional SEM views, enabled the determination of epi-layer thickness, junction depth, and hole diffusion length in the n-type base of the cells.

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Introduction

GaAs solar cells offer the highest efficiency demonstrated to date for space applications, with measured values exceeding 20% (AM0, 137.2 mW/cm^2, 25°C) for cells having an area of 4 cm^2 [ref. 1]. Because GaAs substrates are somewhat fragile, the cell thickness must be appreciable (300 μm) in order for the cell to be durable. Cell weight is a concern because of the rather high density (5.32 g/cm^3) for GaAs.

GaAs cells fabricated on Ge substrates are of interest because the Ge is a rugged material which can be thinned to 75 μm in order to reduce cell weight. In addition, the combination of GaAs on Ge offers the possibility of a tandem cell structure which could make more efficient use of the photons in the AM0 spectrum. GaAs and Ge are well matched both in lattice constant at 300 K (5.653Å for GaAs and 5.646Å for Ge) and in thermal expansion coefficient (5.8×10^{-6}/°C for GaAs and 5.7×10^{-6}/ °C for Ge). This means that high quality GaAs material can be expected in the epitaxial growth of GaAs on Ge substrates. Because GaAs is a direct bandgap semiconductor, only a thin layer (10 μm or less) is required for absorption of the AM0 photons.

The response of GaAs cells fabricated on Ge substrates (GaAs/Ge) to radiation has yet to be explored and compared to the response of GaAs cells fabricated on GaAs substrates (GaAs/GaAs). The purpose of this paper is to report on such a comparative study in which 1 MeV electrons were used to simulate the radiation in a space environment. The cells examined were fabricated by the Applied Solar Energy Corporation under contract to the Air Force. The electron irradiation, annealing, and cell parameter measurements were done at the Westinghouse R&D Center, along with DLTS and EBIC measurements on selected samples. A unique feature of this work is that the electron radiation was administered in doses of 1×10^{16}cm^{-2} to a substantial total of 1×10^{17}cm^{-2} for the GaAs/GaAs cells and to 7×10^{16}cm^{-2} for the GaAs/Ge cells. After each dose, the cells were annealed at either 250°C or 300°C. Such an approach simulates a situation in which the cells are exposed to a heavy dose of radiation (perhaps by passing through the Van Allen belts) and the radiation damage incurred is partially annealed upon return to a base station.

Cell Structure

Both the GaAs/GaAs and the GaAs/Ge cell layers were grown by metal–organic chemical vapor deposition (MOCVD) at the Applied Solar Energy Corporation to form a p on n GaAs active region with an AlGaAs window layer for surface passivation. Layer thicknesses and doping densities for the GaAs/GaAs cell are given in Figure 1. The structure for the GaAs/Ge cell is similar, except that the substrate is Ge which is doped n-type with Sb. The cell is completed with the addition of an antireflective (AR) coating ($TiO_X Al_2O_3$) and contacts to the p-type GaAs emitter (Au Zn Au Ag) and to the n-type GaAs or Ge substrate (Au Ge Ni Au Ag). Further details concerning cell fabrication and structure can be found in references 2 and 3.

Radiation and Annealing Results

In a set of preliminary experiments, two GaAs/GaAs cells were irradiated with 1 MeV electrons and then annealed for 1 hour in nitrogen. It was found that below 200°C no significant increase in cell parameters was obtained and that above 300°C (up to 375°C) only marginal improvement was realized. It was decided, therefore, to carry out the annealing studies at 250°C and at 300°C.

An electron Van de Graaff accelerator at the Westinghouse R&D Center was used for the irradiation which took approximately six hours for a dose of $1 \times 10^{16} cm^{-2}$ (dose rate of $2.8 \times 10^{13} cm^{-2} min^{-1}$). During the irradiation, the cells were moved beneath the electron beam on a conveyer belt so that the temperature of the cells was kept below 40°C. Rapid and accurate dosimetry was accomplished by integrating the charge collected by a Faraday cup which was permanently affixed to the conveyor belt. The charge was directed to a capacitor for integration.

Four groups of cells were selected with six or seven cells in each group. There were two groups of GaAs/GaAs cells (one for the 250°C anneal and one for the 300°C anneal) and two corresponding groups of GaAs/Ge cells. Because the GaAs/Ge cells were not available at the beginning of the experiment, the first three doses of radiation were administered only to the GaAs/GaAs cells. Thus, the GaAs/GaAs cells accumulated a total dose of $1 \times 10^{17} cm^{-2}$ during the course of the study, while the GaAs/Ge cells accumulated only $7 \times 10^{16} cm^{-2}$. All available groups of cells were irradiated together, so that the GaAs/GaAs cells received their fourth increment of radiation at the same time that the GaAs/Ge cells received their first increment. All annealing was done for one hour in a nitrogen ambient.

The effect of each increment of radiation and of each annealing step on short-circuit current density and AM0 efficiency (135 mW/cm^2, 27°C) for the four groups of cells are given in Figures 2, 3, 4, and 5. The data are plotted as averages for each group of six or seven cells, with error bars representing the standard deviation from the average value. A comparison of the GaAs/GaAs cell data with the GaAs/Ge cell data over the full range of radiation dose can be made from these Figures. In addition, key results are given in Table 1 for the four groups of cells as-received, after the first increment of radiation ($1 \times 10^{16} cm^{-2}$), after the first increment and anneal, and after the seventh increment ($7 \times 10^{16} cm^{-2}$) and anneal.

From Table 1 it can be seen that the as-received average values for J_{sc} and V_{oc} are quite similar for the GaAs/Ge cells and the GaAs/GaAs cells. However, the fill factor (FF) is considerably lower for the GaAs/Ge cells than it is for the GaAs/GaAs cells. This low FF is thought to be associated with the interface between the Ge substate and the GaAs epi-layer [ref. 3]. The data of Table 1 show that the GaAs/Ge cells retain a greater fraction of their values of J_{sc}, V_{oc}, and efficiency through all phases of the radiation and anneal than do the GaAs/GaAs cells. In fact, the absolute efficiency of the GaAs/Ge cells exceeds that of the GaAs/GaAs cells after the seventh irradiation ($7 \times 10^{16} cm^{-2}$) and anneal. At this point (Table 1d), the GaAs/Ge cells annealed at 250°C retained 60% of their initial efficiency while their GaAs/GaAs counterparts retained only 42%. Similarly, for cells annealed at 300°C, the GaAa/Ge cells retained 68% of their initial efficiency while the GaAs/GaAs cells retained 48%.

After the first increment of radiation ($1 \times 10^{16} cm^{-2}$, Table 1b), the efficiency of the GaAs/GaAs cells dropped from 16.5% to 4.3%. Thus, only 26% of the as-received efficiency was retained. This is a greater degradation than has been reported in the past. In reference 4, 59% of the average initial efficiency (19.9% to 11.8%) of four MOCVD GaAs/GaAs p on n cells was retained after an exposure to 1 MeV electrons at $1 \times 10^{16} cm^{-2}$. The cells described in reference 4 had a p-type emitter thickness of 0.5 μm. For the GaAs/Ge cells of Table 1b, 39% of the initial efficiency was retained after the first increment of radiation. In an attempt to understand in greater detail the differences between the GaAs/GaAs and the GaAs/Ge cells in this study, and also to understand the rather severe degradation experienced by the GaAs/GaAs cells, some preliminary deep level transient spectroscopy (DLTS) and electron beam induced current (EBIC) measurements were undertaken.

It might be mentioned in passing that a small additional group of four GaAs/GaAs cells was irradiated and annealed at 350°C. The average as-received efficiency of these cells was 17.0%. After the first increment of 1 MeV electron irradiation ($1 \times 10^{16} cm^{-2}$), the efficiency dropped to 29% of its initial value. Annealing at 350°C for one hour in nitrogen raised the efficiency back to 83% of the initial value. After six increments of radiation and 350°C anneal (total dose of $6 \times 10^{16}cm^{-2}$), the cells retained 67% of their initial efficiency with an average efficiency of 11.4%. This is to be compared with a retention of 51% of the initial efficiency for GaAs/GaAs cells annealed at 300°C, and with a retention of 42% for cells annealed at 250°C and subjected to the same total dose. This suggests that an anneal temperature of 350°C may be desirable.

DLTS Measurements

Capacitance DLTS samples were prepared by etching the AR coating from the cells and evaporating 50 nm of Ti and 500 nm of Au on the front surface of the cells using a planetary adapter. Contact between the evaporated metals and the cell emitter was made by way of the grid lines on the cell. Square pieces, 30 mils on a side, were cut from the back of the cell by a laser. These were mounted on T0-5 headers for the DLTS measurement, so the test devices were small p-n junction diodes rather than Schottky diodes. Such diodes had a soft breakdown at approximately 6 V reverse bias. At 4 V reverse bias, however, the leakage current was less than 10 μA, so these samples were suitable for DLTS measurements. The traps in the depletion region were filled with majority carriers when the reverse bias was pulsed from 4 V to 1 V.

Three GaAs/GaAs cells were examined by DLTS. Cell OP-27 had an efficiency of 17.4% (29.0 mA/cm^2, 1.002 V, 0.812 fill factor) when measured as-received. Cell OP-21, with an as-received efficiency of 17.3%, was measured after being irradiated by 1 MeV electrons with a dose of 1×10^{16} cm^{-2} (no anneal) to reduce the efficiency to 4.5% (9.8 mA/cm^2, 0.804 V, 0.780 fill factor). Cell OP-22, with an as-received efficiency of 16.9%, was irradiated with tbe same dose and annealed at 300°C for 1 hour in nitrogen to bring its efficiency to 11.8% (23.6 mA/cm^2, 0.909 V, 0.743 fill factor). The measured DLTS data for these three cells are given in Figure 6.

No deep levels were detected in as-received sample OP-27A, indicating a concentration of such levels below the detection limit of $2 \times 10^{13}cm^{-3}$. One increment ($1 \times 10^{16}cm^{-2}$) of radiation produced two deep levels in sample OP-21B, as shown. Assuming these are majority carrier traps associated with electrons in the n-type base, the positions of the energy levels in the bandgap are at E_c - 0.15 eV and at E_c - 0.62 eV, where E_c is the edge of conduction band. Assuming the base doping is $2 \times 10^{17}cm^{-3}$ [ref. 2], the concentration of these levels is $2.7 \times 10^{14}cm^{-3}$ and $7.8 \times 10^{14}cm^{-3}$ respectively. Annealing of irradiated sample OP-22A reduces the concentration of the E_c - 0.15 eV level to below the detection limit and also reduces the concentration of the E_c - 0.62 eV level to $1.2 \times 10^{14}cm^{-3}$, as shown in Figure 6. Increasing the bias pulse in order to forward bias the p-n junction diode by 1.5 V, thereby injecting minority carriers into the base and emitter, resulted in no additional DLTS peaks beyond those given in Figure 6. Thus, only the two majority carrier electron traps are present in these samples. It appears that the level at E_c - 0.62 eV is responsible for limiting the recovery of cell OP-22 to only 11.4% in efficiency.

Similar results were obtained with a corresponding set of three GaAs/Ge DLTS samples. Cell 135-7 was examined by DLTS as-received, with an efficiency of 16.1%, and no deep levels were detected. Cell 135-R1, which was irradiated with 1 MeV electrons (no anneal) at a dose of $1 \times 10^{16}cm^{-2}$, had an efficiency of 6.3%, and deep levels very similar to those seen in GaAs/GaAs sample OP-21B were observed. A level at E_c - 0.09 eV having a concentration of $1.3 \times 10^{14}cm^{-3}$ was detected, along with a level at E_c - 0.62 eV having a concentration of $5.1 \times 10^{14}cm^{-3}$. The concentration of these levels (again assuming a base doping of $2 \times 10^{17}cm^{-3}$) is less than those measured for GaAs/GaAs sample OP-21B. Finally, GaAs/Ge cell 135-R2, which was irradiated at

$1 \times 10^{16} cm^{-2}$ and annealed at 300°C for 1 hour in nitrogen to give an efficiency of 13.6%, behaved similarly to GaAs/GaAs cell OP-22A in Figure 6c. The concentration of both levels was significantly reduced, with the E_c - 0.09 eV level sinking below the detection limit ($2 \times 10^{13} cm^{-3}$) and the E_c - 0.62 eV level reduced to $1.4 \times 10^{14} cm^{-3}$. There does not appear to be a significant difference in the DLTS spectra of the GaAs/GaAs cells and the GaAs/Ge cells.

Radiation damage caused by 1 MeV electrons is one of displacement, where Ga and As atoms are displaced from their equilibrium positions by the energetic electrons. This means that the defects created are likely to be vacancies (Ga or As), interstitials (Ga or As), antisite defects (Ga on As site or As on Ga site), or perhaps complexes of point defects including impurity atoms. Unfortunately, the association of a DLTS level with a particular crystalline defect cannot yet be made with certainty. The level observed at E_c - 0.62 eV (Figure 6b) is close in energy to the EL2 level in GaAs, which is a deep donor at E_c - 0.67 eV [ref. 5]. This level is often intentionally introduced during GaAs crystal growth to make the crystal semi-insulating. It is thought to be associated with a Ga vacancy or an antisite defect caused by an As atom occupying a Ga site. The level observed at E_c - 0.15 eV may be associated with the displacement of an As atom. In any event, only two deep levels were observed in this work. Earlier DLTS studies of GaAs irradiated by 1 MeV electrons have shown as many as 5 electron traps and 2 hole traps [ref. 5]. The situation may be simpler in the present study because of higher purity GaAs material, with fewer impurity atoms present to join in forming electrically active complexes.

EBIC Measurements

The EBIC measurements were made using an AMRAY Model 1635 scanning electron microscope and associated electronics. The energy of the electron beam was 30 keV. GaAs/GaAs cell OP-50 was examined as received. This cell had an efficiency of 17.0% (29.0 mA/cm^2, 0.996 V, and 0.805 fill factor) and was cleaved to expose a clean cross-section. The epi thickness was found to be 10.5 μm for this sample. A cross-sectional EBIC scan is shown in Figure 7a. Three distinct regions of the cell can be discerned from the scan. From the external surface, the linear region is the p-emitter, the relatively flat peak is the depletion region, and the exponential fall-off is the n-base.

The junction depth is 0.80 μm from the external surface. Assuming the AlGaAs window layer is 0.1 μm thick [ref. 2], the GaAs emitter is 0.70 μm in depth. This may explain the relatively poor radiation tolerance of these cells. According to reference 6, an emitter thickness of 0.70 μm is expected to lead to a reduction in efficiency to approximately 25% of the initial efficiency following a 1 MeV electron dose of $1 \times 10^{16} cm^{-2}$ This is in good agreement with the values observed (Table 1). The hole diffusion length in the n-base can be estimated from tbe exponential profile of Figure 7a as 3.7 μm.

For comparison, a cleaved cross-section of GaAs/Ge cell 6 was also examined by EBIC and is shown in Figure 7b. This cell had undergone one increment of electron irradiation ($1 \times 10^{16} cm^{-2}$) and an anneal at 250°C for one hour in nitrogen prior to the EBIC measurement. After the irradiation and anneal the efficiency was 11.3% (25.6 mA/cm^2, 0.960 V, 0.618 fill factor), which was 83% of the initial efficiency of 13.5%. In this case the GaAs epi thickness was only 3.8 μm, significantly less than the 10.5 μm thickness for cell OP-50 in Figure 7a. The diffusion length of holes in the n-base of GaAs/Ge cell 6 appears to be limited by the epi thickness of 3.8 μm, since the fall-off of the EBIC signal in the base is nearly linear.

The depth of the junction from the surface for cell 6 is 0.71 μm from Figure 7b. Again assuming an AlGaAs window thickness of 0.1 μm, the GaAs emitter is then 0.61 μm in depth. This is somewhat better than the 0.70 μm found for GaAs/GaAs cell OP-50, and may be partially responsible for the improved radiation tolerance of the GaAs/Ge cells relative to the GaAs/GaAs cells. This assumes that the junction depths estimated for the cells of Figure 7 are representative for the cells of Figures 2 to 5. According to reference 6, the junction depth must be less than 0.5 μm (preferably 0.3 μm or less) in order to obtain a high degree of radiation tolerance.

Conclusions

The GaAs/Ge cells are somewhat more tolerant of 1 MeV electron irradiation and more responsive to annealing than are the GaAs/GaAs cells examined in this study. However, both types of cells suffer a greater degradation in efficiency than has been observed in other recent studies. The reason for this is not certain, but it may be associated with an emitter thickness which appears to be greater than desired. DLTS spectra following irradiation are not significantly different for the GaAs/Ge and the GaAs/GaAs cells, with each having just two peaks. The annealing behavior of these peaks is also similar in the two samples examined. It appears that no penalty in radiation tolerance, and perhaps some benefit, is associated with fabricating MOCVD GaAs cells on Ge substrates rather than GaAs substrates.

References

[1] R. E. Hart, Jr., NASA-Lewis Research Center, private communication.

[2] P. A. Iles, K. I. Chang, and W. Pope, "Review of MANTECH Program for GaAs Solar Cells," *Conf. Rec. 19th IEEE Photovoltaic Specialists Conf.* (87CH2400-0) (New Orleans, LA), p. 331, 1987.

[3] K. I. Chang, Y. C. M. Yeh, P. A. Iles, J. M. Tracy, and R. K. Morris, "Heterostructure GaAs/Ge Solar Cells", *Conf. Rec. 19th IEEE Photovoltaic Specialists Conf.* (87CH2400-0) (New Orleans, LA), p. 273, 1987.

[4] H. C. Hamaker, J. G. Werthen, C. R. Lewis, H. F. MacMillan, C. W. Ford, G. F. Virshup, R. K. Ahrenkiel, D. L. Greenberg, and J. Schlupmann, "Radiation Damage of 1.93-eV $Al_{0.37}Ga_{0.63}As$ and GaAs Solar Cells Grown by Metalorganic Chemical Vapor Deposition", *Conf. Rec. 19th IEEE Photovoltaic Specialists Conf.* (87CH2400-0) (New Orleans, LA), p. 733, 1987.

[5] A. G. Milnes, "Impurity and Defect Levels (Experimental) in Gallium Arsenide", in *Advances in Electronics and Electron Physics, Volume 61,* edited by P. W. Hawkes, Academic Press, New York, 1983 (pp. 64-160)

[6] R. Loo, G. S. Kamath and R. C. Knechtli, "Radiation Damage in GaAs Solar Cells", *Conf. Rec. 14th IEEE Photovoltaic Specialists Conf.* (80CH1508-1) (San Diego, CA), p. 1090, 1980.

Table 1. **Average GaAs Cell Parameters for Each of the Four Groups at Key Points in the Irradiation/Anneal Sequence**

Substrate	Temperature (°C)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
a) As-received					
GaAs	250	28.8	0.997	0.776	16.5
Ge	250	29.1	1.007	0.631	13.6
GaAs	300	28.8	1.004	0.772	16.5
Ge	300	29.3	0.996	0.606	13.1
b) Immediately after first irradiation of 1 MeV electrons (1×10^{16} cm^{-2})					
GaAs	250	9.7	0.802	0.773	4.4
Ge	250	11.7	0.924	0.657	5.3
GaAs	300	9.5	0.800	0.754	4.2
Ge	300	11.9	0.914	0.624	5.0
c) After first irradiation (1×10^{16} cm^{-2}) and anneal (1 hour in N_2)					
GaAs	250	21.4	0.856	0.775	10.6
Ge	250	25.7	0.975	0.609	11.3
GaAs	300	24.0	0.911	0.748	12.1
Ge	300	26.4	0.989	0.567	11.0
d) After seventh irradiation (7×10^{16} cm^{-2}) and anneal (1 hour in N_2)					
GaAs	250	16.0	0.802	0.726	6.9
Ge	250	19.6	0.938	0.600	8.3
GaAs	300	17.4	0.840	0.734	8.0
Ge	300	21.9	0.973	0.559	8.9

Measurement Conditions: AM0, 135 mW/cm^2, 27°C

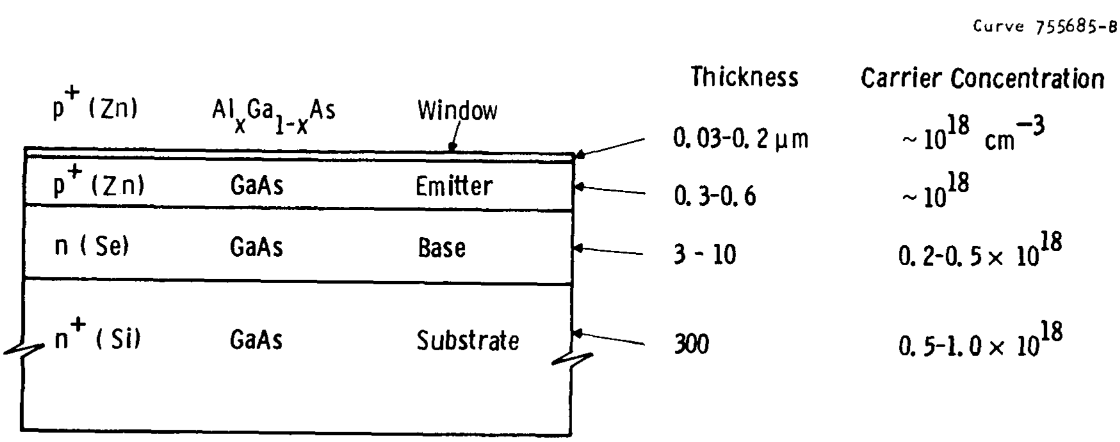

Fig. 1—GaAs/GaAs structure following MOCVD layer growth

Curve 755683-B

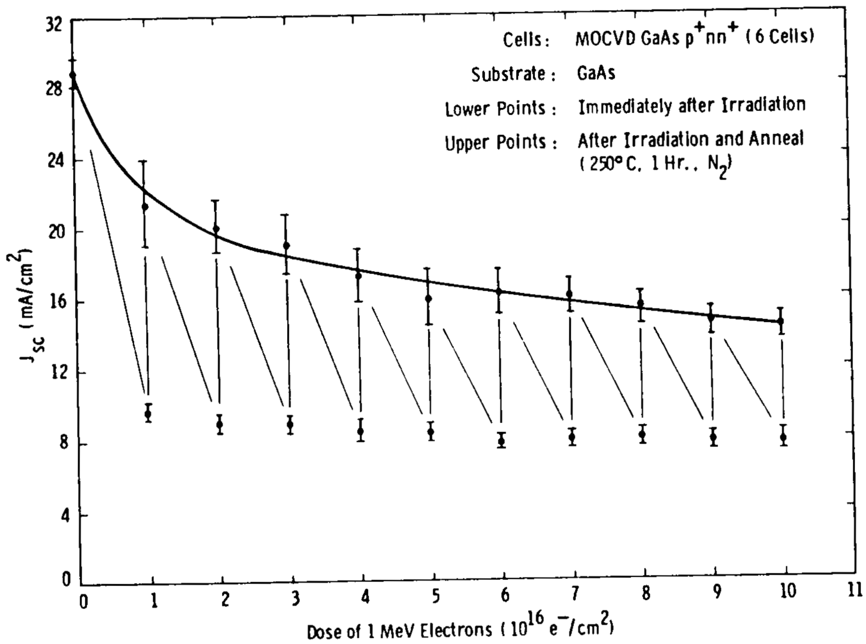

Fig. 2a—Effect of electron irradiation and 250°C anneal on short-circuit current density of GaAs/GaAs cells. (Cells OP-1, OP-2, OP-4, OP-5, OP-7, OP-8)

Curve 755684-B

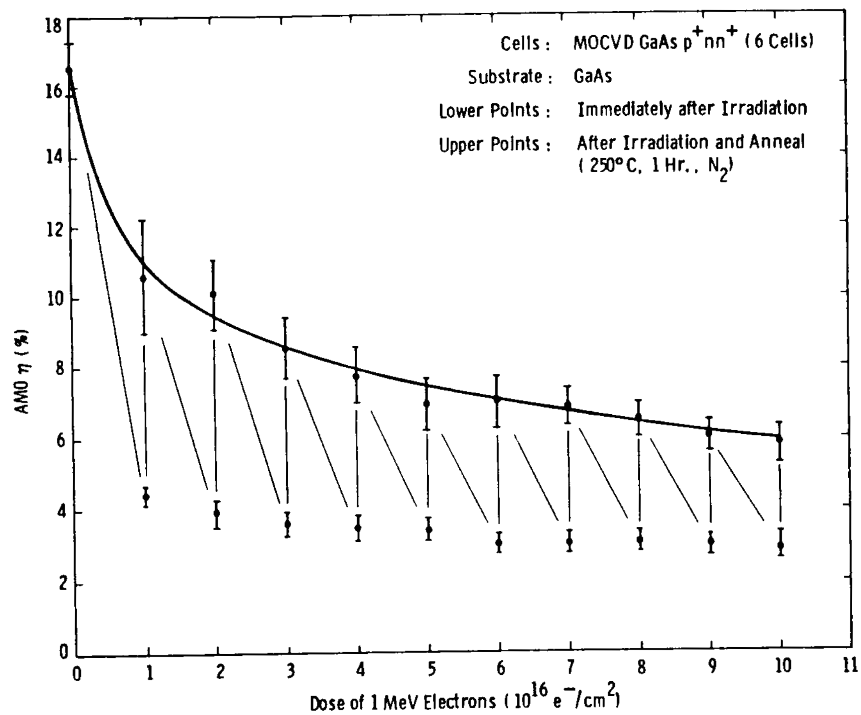

Fig. 2b—Effect of electron irradiation and 250°C anneal on AMO efficiency of GaAs/GaAs cells. (Cells OP-1, OP-2, OP-4, OP-5, OP-7, OP-8)

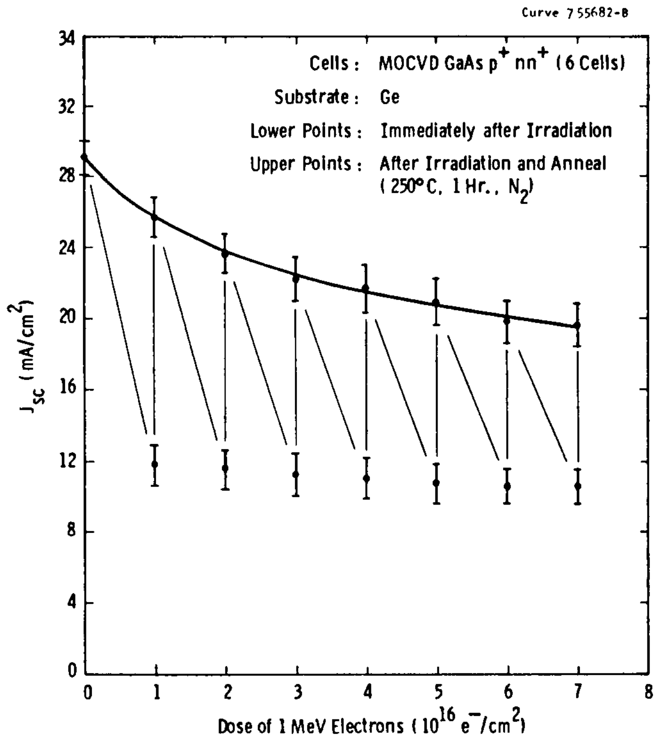

Fig. 3 a—Effect of electron irradiation and 250°C anneal on short-circuit current density of GaAs/Ge cells. (Cells 2, 3, 4, 7, 135-8, 135-9)

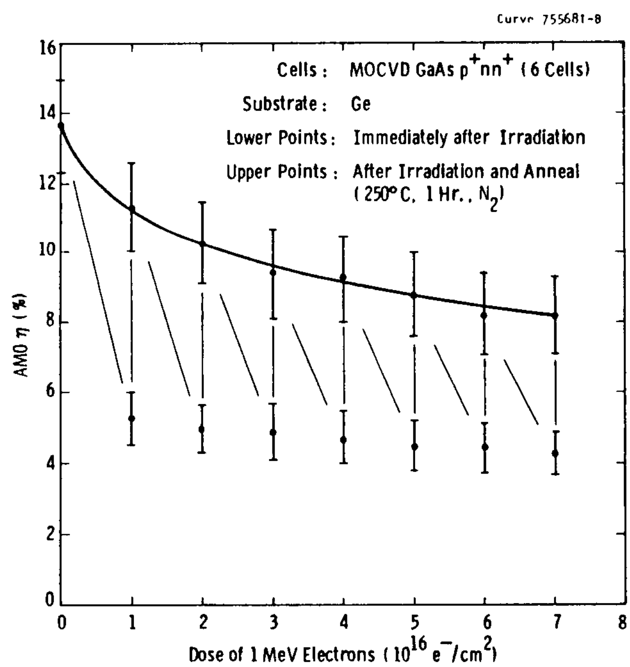

Fig. 3b—Effect of electron irradiation and 250°C anneal on AMO efficiency of GaAs/Ge cells. (Cells 2, 3, 4, 7, 135-8, 135-9)

Curve 755680-B

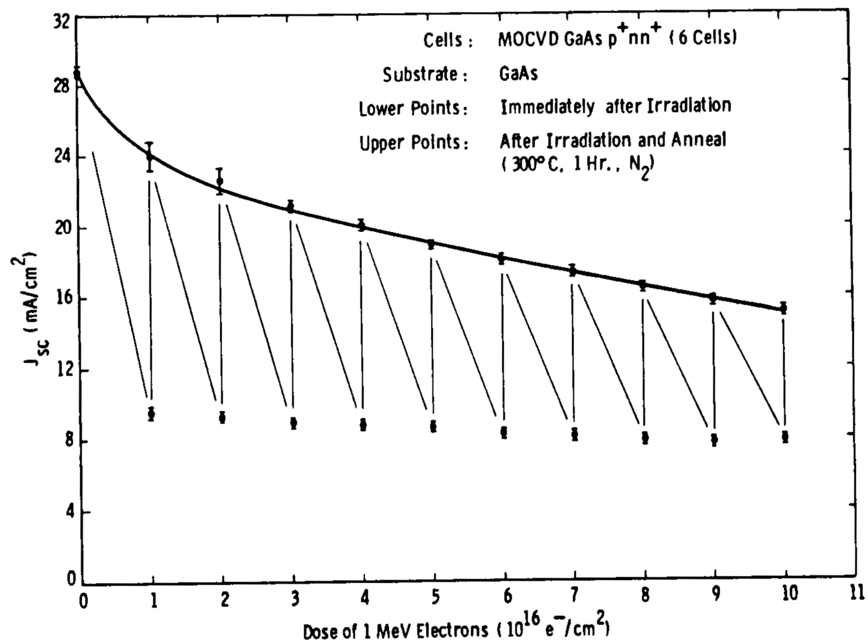

Fig. 4a—Effect of electron irradiation and 300°C anneal on short-circuit current density of GaAs/GaAs cells. (Cells OP-11, OP-12, OP-13, OP-16, OP-17, OP-19)

Curve 755679-B

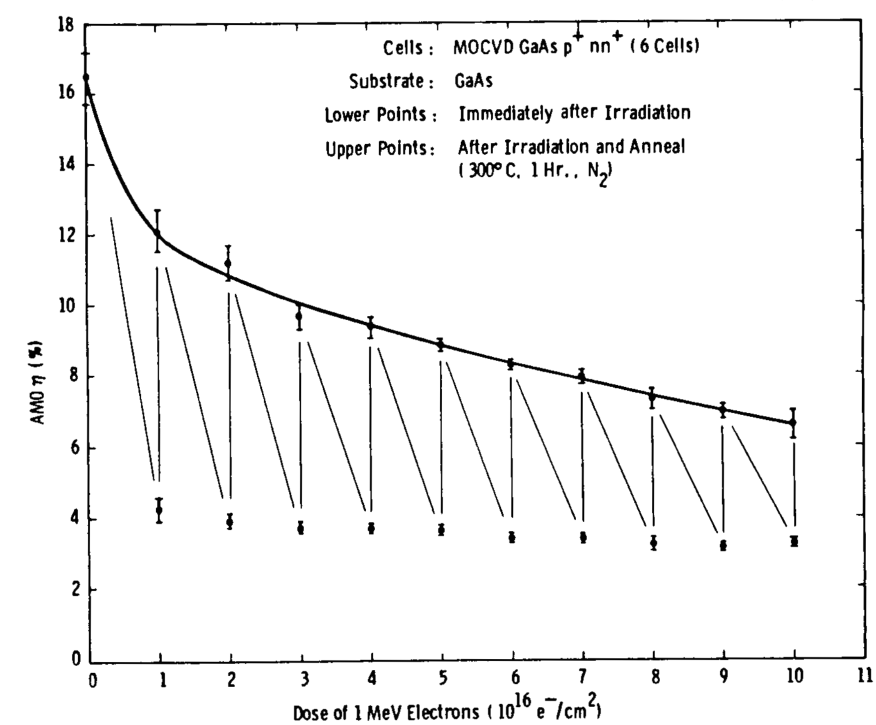

Fig. 4b—Effect of electron irradiation and 300°C anneal on AM0 efficiency of GaAs/GaAs cells. (Cells OP-11, OP-12, OP-13, OP-16, OP-17, OP-19)

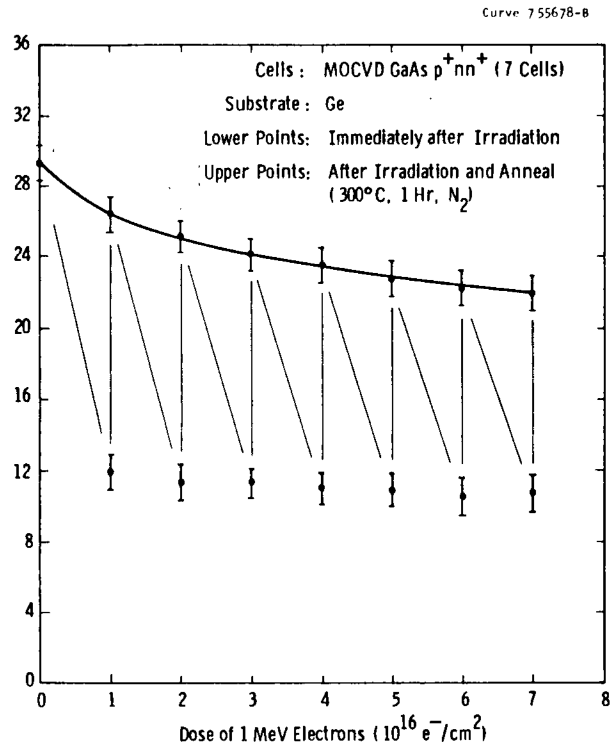

Fig. 5a—Effect of electron irradiation and 300°C anneal on short-circuit current density of GaAs/Ge cells. (Cells 10, 11, 12, 14, 15, 135-10, 135-12)

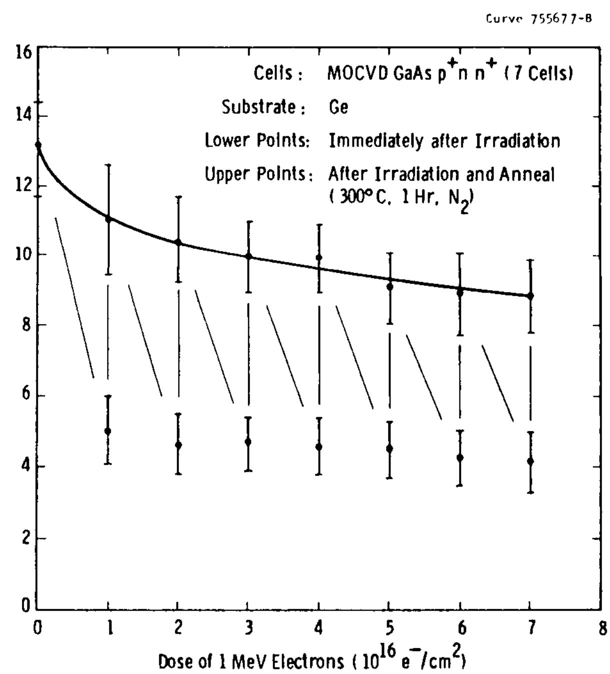

Fig. 5b—Effect of electron irradiation and 300°C anneal on AM0 efficiency of GaAs/Ge cells. (Cells 10, 11, 12, 14, 15, 135-10, 135-12)

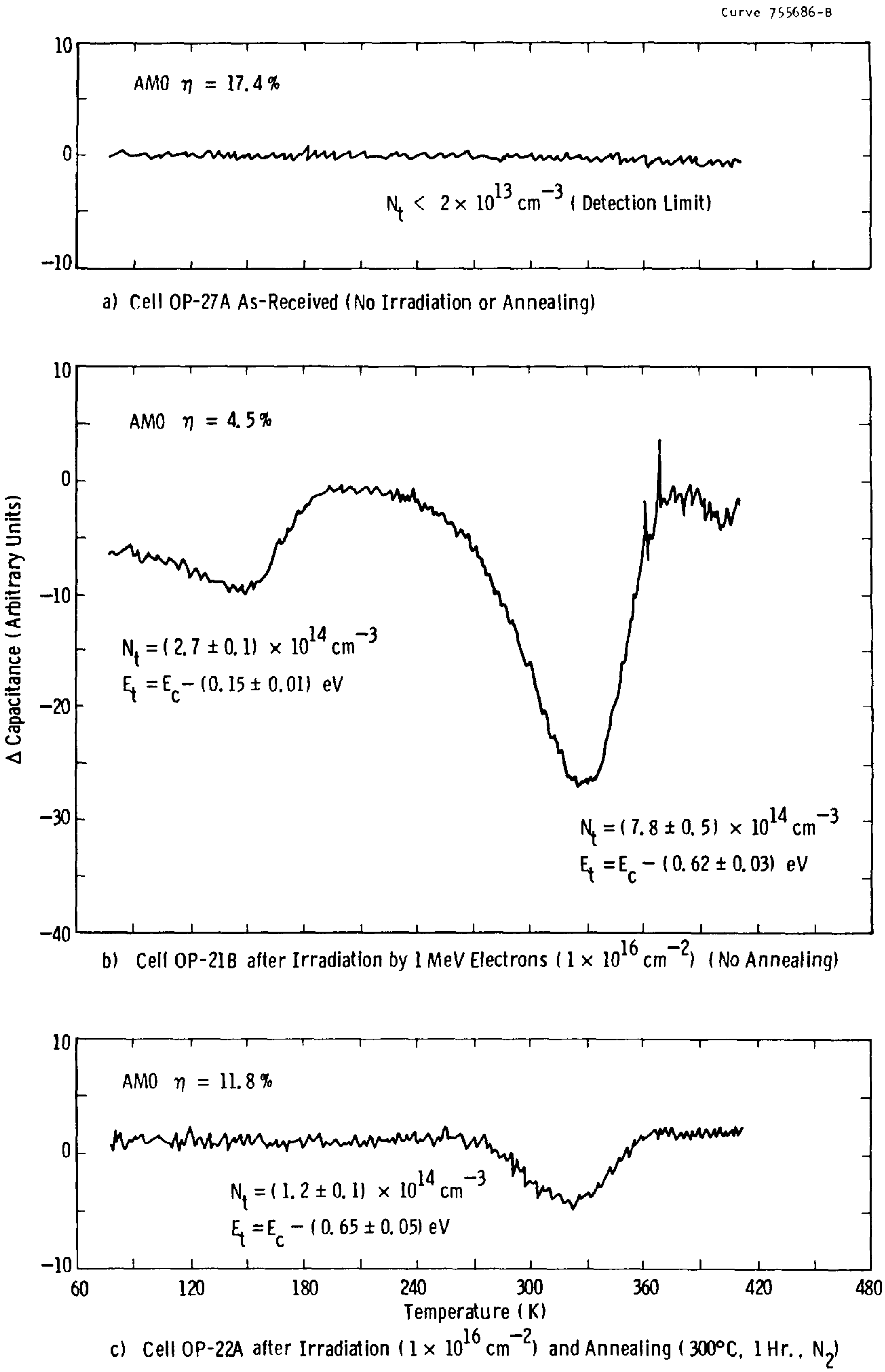

Fig. 6—DLTS scans for GaAs/GaAs cells showing the creation and subsequent annealing of deep levels from 1 MeV electron irradiation

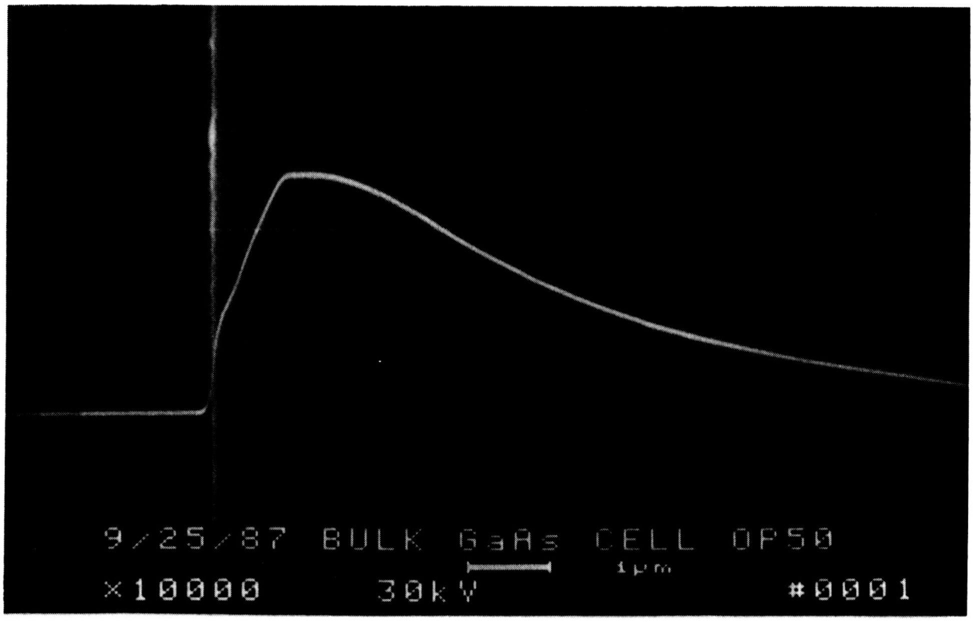

Figure 7a — EBIC scan of GaAs/GaAs cell with 10.5 µm epi thickness showing 0.80 µm junction depth and 3.7 µm base diffusion length.

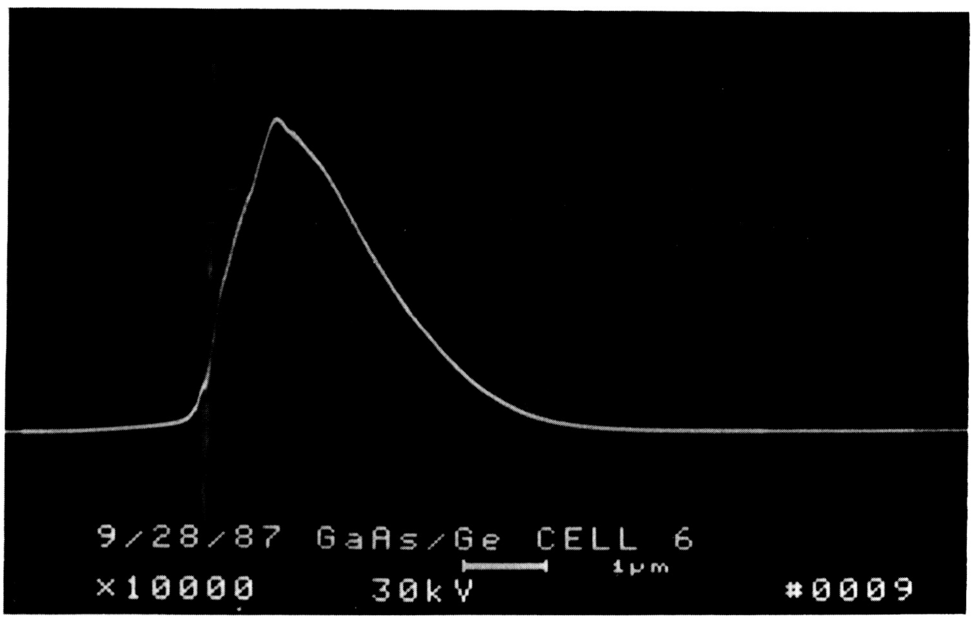

Figure 7b — EBIC scan of GaAs/Ge cell with 3.8 µm epi thickness showing 0.71 µm junction depth and base diffusion length apparently limited by epi thickness.